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Optoelectronic Components and Integrated Circuits including Up and Down Conversion Technique and Hybrid Integration Technology

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Summary

Microwave optical links can be considered as basic bricks for some emerging system applications such as optically supplied microwave antennas... Emitters, optical switching matrices, high speed photodetectors and specific components for up or down conversion, are generic devices or functions for microwave optical links. We will describe main ways to generate microwave or millimetre wave signals through an optical fibre: direct and external modulation, optical control of microwave oscillators, generation of harmonics with laser non-linearities, dual mode emitters, with emphasis on new explored ways. Optical switching matrixes, which are basic photonic integrated circuits for optical processing are also examined, with recent cross-talk and phase noise results. The problem related to high speed photodetectors are also detailed with emphasis on waveguide photodetectors. The problem of up and down conversion is developed through specific optoelectronic devices. At last, we discuss the monolithic integration of optoelectronic or photonic devices, recalling that the industrial way is based on hybrid technology on silicon mother board, and we suggest new ways for the future.

1. Introduction

Microwave optical links can be considered as basic bricks for some emerging system applications such as optically supplied microwave antennas. Here we will focus our attention on emitters, switching matrices, and high speed photodetectors which can be considered as generic devices or functions for microwave optical links. The last section will be devoted to the crucial problem of the integration (hybrid versus monolithic) of components and circuits.

2. Emitters

There is a lot of techniques to generate a microwave or millimetre wave signal through an optical fibre. We present and discuss here several of them with examples of specific devices developed for the purpose.

2.1 Direct modulation of laser diode

This is the most simple and popular method. This approach is based on the modulation of the current injected into a laser diode. The frequency response is characterized by a resonance effect which frequency increases with the injected current. Bandwidth above 20 GHz have been achieved with InP DFB lasers using this technique, but the bias current is generally high (over 100 mA). These operation conditions degrade the performance of the microvave optical link, particularly in terms of dynamic.

Other modulation approaches are explored in order to overcome this limitation. A new concept proposed a few years ago is based on the parametric modulation. The principle is the modulation of the absorption in a

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small part of the cavity, instead of modulation via the injected current, as usually made. To achieve such a goal, the cavity of the semiconductor laser is separated into two parts: one is devoted to the laser gain, and the second to the modulation (figure 1). It means that the p+ upper electrode of the laser is separated into these two parts: a long one for gain purpose on which a current is injected, a short one for modulation on which the microwave signal is applied. These two electrodes must be electrically isolated. Compared to dynamic response of classical semiconductor laser, theoretical results [1] predicted a strong enhancement of the resonance effects at the same frequency, with a lower decrease of the dynamic response at high frequencies, 20 dB instead of 40 dB per decade (figure 2).

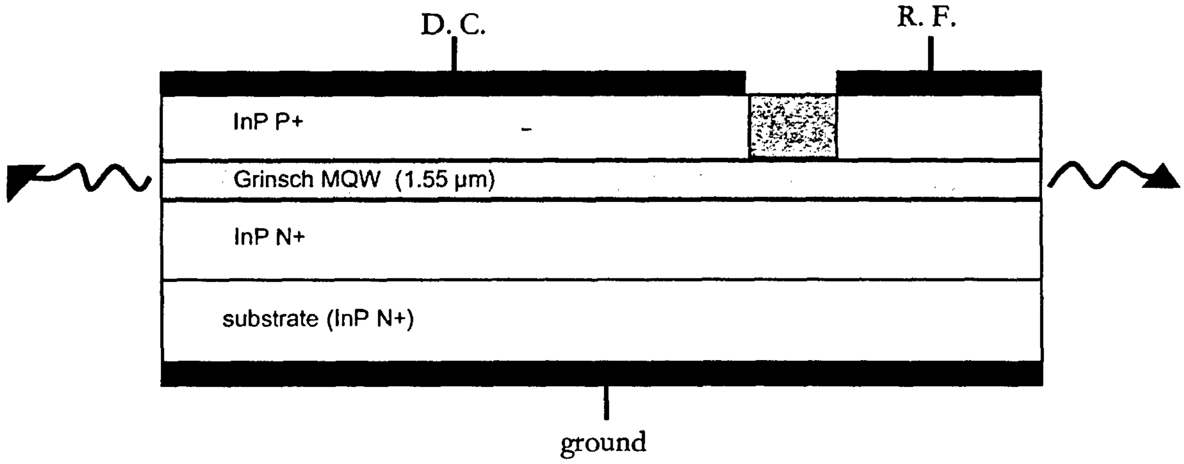


Figure 1 : Two electrode laser diode for parametric modulation.

This device was fabricated at Thales TRT. It was an InP MQW DFB laser with two electrodes (same axis) electrically isolated. Much attention was given to the isolation obtained by etching, and also to get low parasitic contact resistance and capacitance of the short length modulation zone. Experimental results confirmed theoretical predictions with the demonstration of a cut-off frequency over 30 GHz [2].

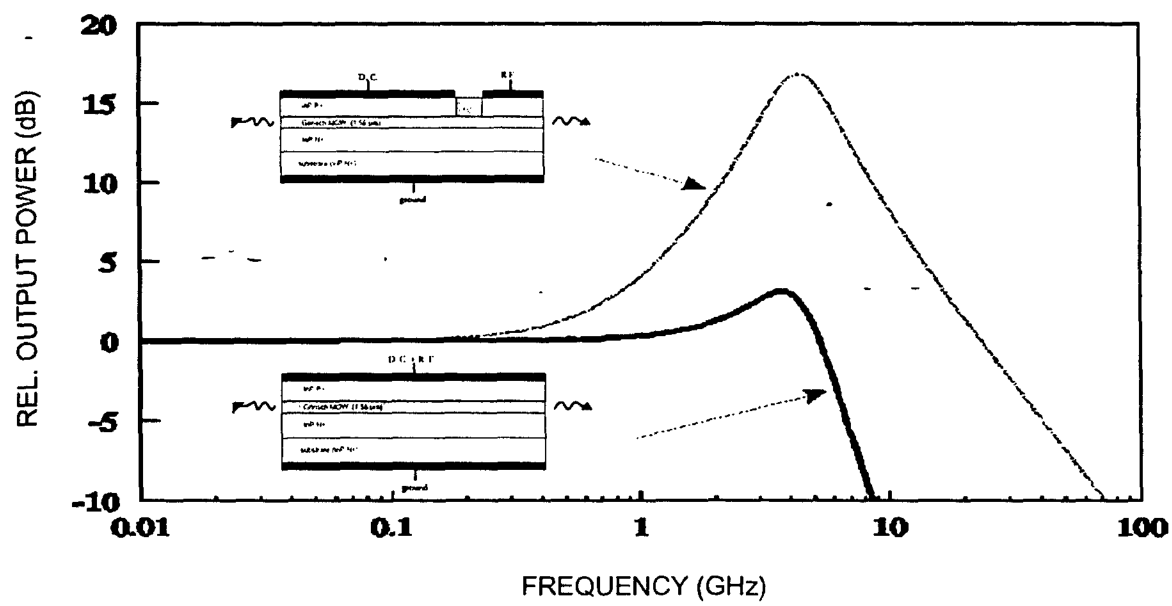


Figure 2 : Direct modulation and parametric modulation characteristics of semiconductor laser diodes.

An alternative to this approach is the laterally coupled dual laser. This new solution is currently studied in the frame of the FALCON TMR European project (coordination: prof. H. Lamela, university Carlos III –

Madrid). The principle is here to integrate inside the same laser cavity two parallel active zones. The first fabricated prototype is a 1.3 µm MQW InP Fabry-Perot laser with two active regions defined by the two parallel electrodes and by rib etching of the upper layer to get the optical confinement (figure 3). Depending on the distance between the two ribs, the optical coupling between the two laser active zones can be adjusted.

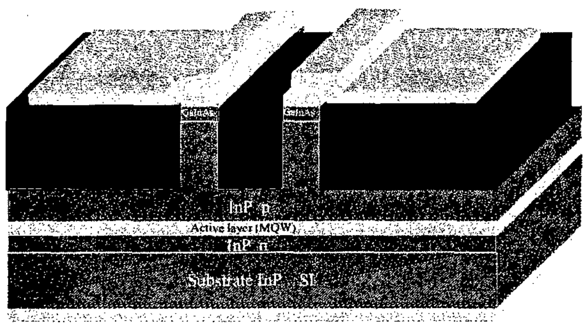


Figure 3 : Schematic view of a laterally coupled semiconductor laser.

It was theoretically predicted that a strong enhancement of the bandwidth could be achieved by applying the modulation current to one electrode and a DC current to the other one [3]. The bandwidth enhancement can be explained by a phenomenon similar to the bandwidth increase of coupled oscillators. First experimental results do not confirm theoretical bandwidth improvements. But a splitting of the optical modes into two lines could be observed, the frequency separation depending on the electrodes biasing. This result can be used to generate a microwave signal through the beating of the two optical modes into a high speed photodetector. In this experiment, the frequency of the microwave signal could be tuned with the bias currents injected into each active zone of the dual laser. The microwave signal frequency increased with the difference between the two bias currents and was only limited by the cut-off frequency (18 GHz) of the high speed photodetector. Nevertheless, due probably to the Fabry Perot multimode operation, the microwave signal was not pure enough to be useful and DFB structures seem to be promising.

2.2 External modulation:

It is an interesting alternative to direct modulation. For this scheme a CW current is injected into the laser diode and the modulation is applied to an external optical modulator. As a consequence the best (bias) conditions can be used for each function (emission and modulation). To improve the noise, hence the dynamic of the link, solid (YAG) lasers can advantageously replace the semiconductor (DFB) laser, if no limitation in place is required. Among the effort to increase the performance of the optical modulators, the bandwidth is an important feature. We can class modulators in two main types: electro-absorption and electro-optic modulators. For the first type an electric field, modifies the transparency (or absorption) of a III-V material for an optical signal wavelength close to its bandgap wavelength. Thanks to Franz Keldish effect a change of bandgap energy occurs under applied voltage and for a good choice of signal wavelength, the semiconductor material changes its transmission state from transparent to absorbing. Multiquantum well PIN structures introduced into optical waveguides are used to increase this phenomenon (Quantum Confined Stark Effect). With this kind of devices bandwidth above 40 GHz are obtained, combined to a modulation voltage close to 1 V. The efficient modulation / voltage ratio is a consequence of a (resonant) exitonic effect and thus the optical bandwidth of the modulator is limited to several 10 nm. In spite of a low modulation voltage, which makes these devices attractive, they are in general strongly nonlinear and the quality of the microwave optical link can be degraded.

It is the reason why electro-optic modulators, based on the modulation of the phase of the optical signal via the electro-optic Pockels effect, is also under studies. To get an amplitude modulation, the electro-optic device is based on the principle of the Mach-Zehnder interferometer: the optical signal is divided into two arms (equal length) and recombined at the output. The device is fabricated in integrated optics, with an electrooptic material. Electrodes are placed along one (or both) arms. When a voltage is applied to one arm, a corresponding optical phase change is obtained; if the difference of phase at the output of the two arms is π, a null occurs (which defines V_π voltage). Different materials are used: $LiNbO_3$, III-V, polymers... $LiNbO_3$

exhibits the highest optical index variation with electric field. Even in this case, the electrode must be long (over 1 cm) to get a V_π voltage still rather high (~10V). The consequence is a high capacitance, and the only solution to overcome this fundamental limitation is the travelling wave electrode. The basic idea is here to transform the long electrode into a 50 Ω transmission line loaded on a 50 Ω impedance. In principle, if the optical and microwave indices are equal, the bandwidth is unlimited. This is difficult to achieve with $LiNbO_3$ because the microwave permittivity is far from the square of the optical index; for III-V materials the condition optical index # microwave index is verified but these materials suffer from a lower electro-optic effect. Polymer based modulators are under intense research because optical and microwave indexes are equal and polymer can be deposed on metal leading to, in principle, ideal microwave microstrip lines. Electro-optic effect is induced by chromophores introduced in the polymer. To get an electro-optic activity, a poling procedure is carried out. Bandwidth over 40 GHz are obtained with the three types of materials. Due to a special electrode design ($LiNbO_3$ modulators) or advanced materials (polymer modulators), low V_π (< 1 V) and high bandwidth electro-optic modulators are demonstrated [4, 5].

2.3 Optical control of microwave oscillators :

It consists of modifying the characteristics (amplitude, phase or frequency) of a millimetre wave signal generated by the oscillator, thanks to the optical signal impinging on the oscillator. It is also possible, to optically lock the frequency of the microwave oscillator. In optical injection locking, the optical control signal is intensity modulated at a frequency close to the free running frequency of the oscillator (fundamental locking), one of its harmonics (harmonic locking), or one of its subharmonic (subharmonic locking) [6]. The modulated optical signal absorbed in the device active region gives rise to a current flow at the modulating frequency, and this acts in a very similar way to direct microwave signal injection. The use of subharmonic locking is suggested by the inherent nonlinearity of the active devices composing the oscillator, and it allows to use a diode laser which cut-off frequency is far below the frequency of the microwave oscillator (also with the possibility to neglect fibre dispersion effects). A fibre radio link was recently demonstrated based on this principle, with 7.6 dBm microwave output power, the oscillator being locked using up to the 32th subhamonic. The frequency was 10.6 GHz and the wavelength was 0.8 µm, the link being composed of a GaAs VCSEL and a GaAs MMIC [7]. Because this technique is promising for simplicity, power, conversion efficiency, intensive research are devoted to this topic for 1300 and 1550 nm operation, or for example at University of Kent at Canterbury.

2.4 Generation of harmonics with laser non-linearities:

When biased under high current or modulated at a frequency close to the resonance frequency, a laser diode is generally highly non-linear. This effect can be advantageously used to get harmonics of the modulating microwave signal at the output of the link, if the speed of the photodetector is high enough and the length of fibre low enough to overcome bandwidth limitations due to fibre dispersion effects. In practice, the laser bias current is adjusted to match the resonance frequency of the laser to the microwave modulating frequency to improve harmonics generation ; an electrical filtering at the output of the photodetector allows to select the good harmonic. In terms of phase noise, the degradation (20.Logn, where n is the rank of the harmonic) is similar to a system based on the transmission of the fundamental through the link and electrically multiplied at the output, (or other systems based on a reference multiplication). For both cases, fibre-radio systems were demonstrated [8, 9], the second solution being more tolerant to the fibre dispersion, but a more complex microwave circuit (MMIC) is required. In principle this method could be extended to non-linear photodetectors. But a photodetector (except for very small ones) is a very linear component compared to a laser diode. Non-linear photodetector behaviour needs high optical power and low bias voltage and in practice in a link, laser diodes non-linearities appear before photodetector ones.

2.5 Dual mode emitters:

Another class of the optical microwave or mm-wave generation techniques is based on the emission of an optical spectrum consisting of only two discrete tones, separated by the mm-wave frequency. Mixing the two phase-correlated tones at a square low photodetector provides a spectrally pure mm-wave carrier signal at frequency f_{mm}. Fiber dispersion only affects the phase of the detected mm-wave signal, and this approach can operate over arbitrary lengths of standard fibre at 1550 nm.

A well-known system is the one adopted within the FRANS project, supported by the European Commission ACTS programme, and developed within the RACE project MODAL [10]. This technique generates a two-tone optical signal using a Mach-Zehnder modulator as an electro-optic mixer. Knowing that the Mach-Zehnder Modulator has a raised cosine intensity response, when biased at the point of minimum optical transmission, the response of the device on the optical field can be written as : $E_{out} = E_{in} \sin(\pi V/2V_\pi)$ [11], leading to two optical modes.

Among the number of approaches which have been proposed and demonstrated to optically generate mm-wave signals [see for example 12 – 32], a very promising solution based on optical heterodyning, was developed at BT Laboratories. It consists of a master-slave Distributed Feedback (DFB) laser arrangement, where the lasers are in a series configuration and each laser contributes a single mode for optical mixing in a high speed photodiode [25, 32]. The electrical drive to the slave laser is at a subharmonic of the beat frequency and generates a series of sidebands. The master laser mode injection locks one of these slave sidebands which results in phase noise cancellation in the output signal.

It is also interesting to mention the works on optical Single Side Band generation to overcome penalties in fibre radio system with data signal. It has been demonstrated that, by using an optical filter to suppress one of the sidebands [33], in intensity modulation schemes, dispersion effects can be reduced by the elimination of one sideband to produce an optical single-sideband. This method is limited by the filter characteristics and can be quite complex to implement. To eliminate the need of optical filtering, a novel technique recently proposed [29] uses only one dual-electrode Mach-Zehnder Modulator. The RF signal is applied to both electronics with $\pi/2$ phase shift applied to one electrode. A DC bias voltage is also applied to one electrode while the other DC terminal is grounded. The Mach-Zehnder modulator can be considered as two optical phase modulators in parallel with drive signal $\pi/2$ out of phase and with DC voltage applied to one arm. By tuning the DC voltage, modulator is biased at quadrature. The RF power degradation due to fibre dispersion was observed to be only 1.5 dB when using the technique to send 2 – 20 GHz signals over 79,6 km of fibre. Approximately at the same time, fully integrated millimetric single sideband lightwave source were demonstrated [30] increasing the attractiveness of this technique.

Obviously the disposal of monolithic integrated dual mode sources is interesting for compactness, reduction of parasitics, efficiency... One way, as said just before [30], is the monolithic association of a DFB laser and a specially designed external optical modulator. One other way is the dual mode laser. DFB laser structures for which the usual effort to lift the mode degeneracy was not taken into consideration are dual mode laser. The coupling coefficient and the total laser length are the two main parameters governing the frequency separation between the two modes. The mode separation is approximately given by the following expression: $\Delta f \sim 1.5\, c\, \kappa \sqrt{2 / (\pi\, n_e \tanh(\kappa L))}$

Where Δf is the mode frequency separation of the DFB ; κ the coupling coefficient of the DFB structure and L the total laser length. For a 60 GHz mode separation for example, we need a 2 mm long laser with a 9 cm^{-1} coupling coefficient. To reduce the laser length we need to reduce the coupling coefficient as well (below 3 cm^{-1} for a 1 mm long laser). But it seems difficult to control such reduced coupling coefficients from a technological point of view and the laser could possibly turn into a multimode emission. A possible structure designed with the aim of reducing the "effective" coupling coefficient using usual technologies compatible with conventional coupling coefficients, consists of alterning DFB and FP sections pumped by a single section source (figure 4). Using such a structure we can expect to get a reduced effective coupling coefficient by increasing the FP section length. A square wave function will sample the DFB structure according to its duty cycle. So, the refractive index of this structure will be equal to the refractive index of the conventional DFB multiplied by the Fourier series expansion of the spatial square wave function. It turns out that instead of having a single reflection coefficient centred around the Bragg frequency, this structure will generate a periodic filter with a periodicity in terms of optical frequency.

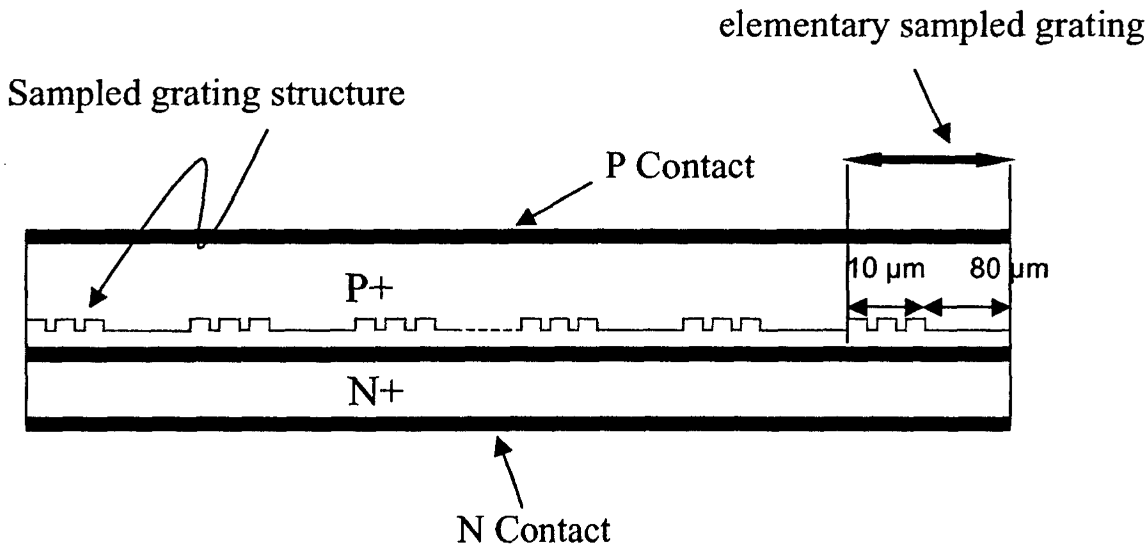


Figure 4 : Schematic of a dual mode laser based on a sampled grating structure.

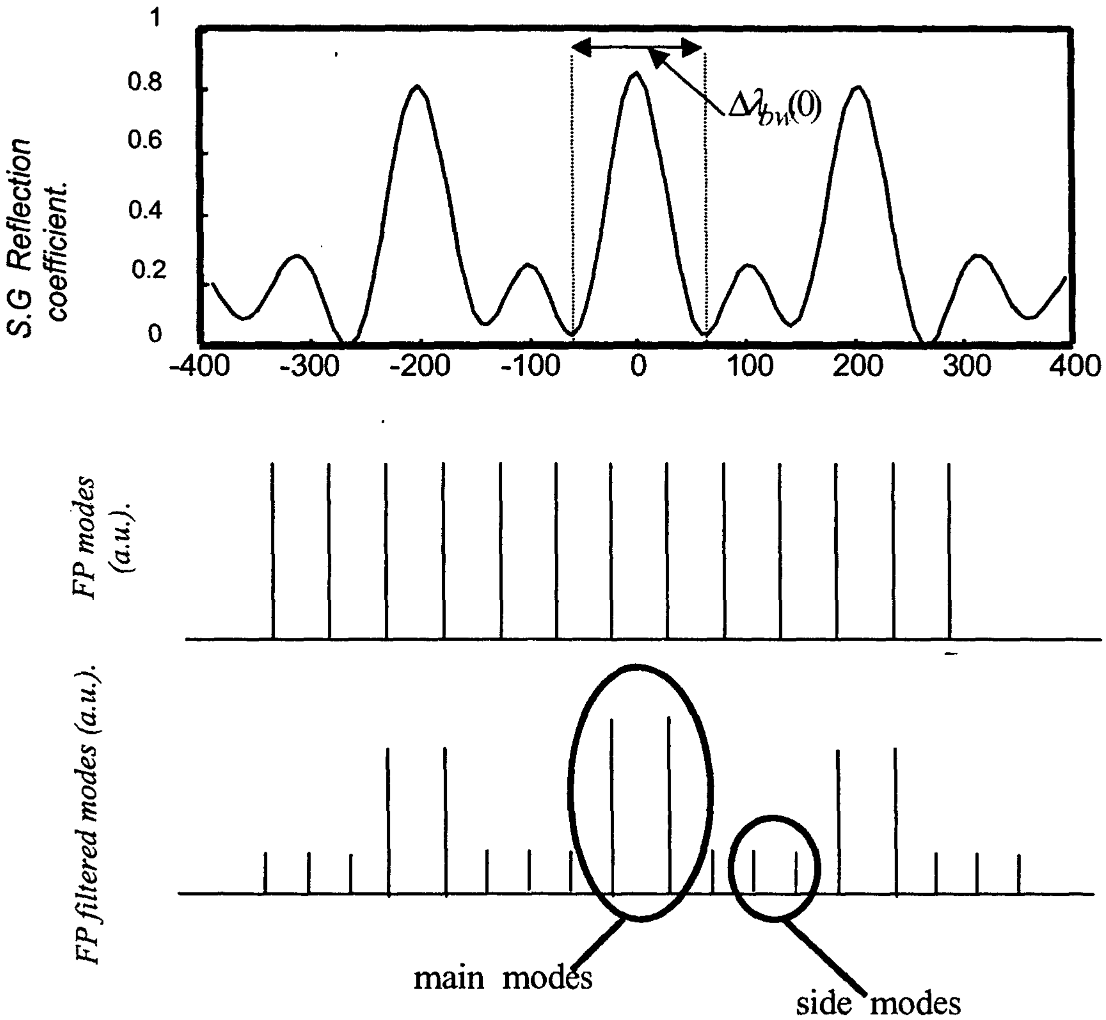


Figure 5 : Filtering of the Fabry Perot modes by the sampled grating periodic filter.

This can be illustrated by the schematic given in figure 5 where we show the modes of a Perot Fabry cavity and we superimpose the filter due to the periodic DFB section. Such a structure was modelled using the time domain model. It was shown that a good design of this structure predicts theoretically a dual mode emission with 60 GHz optical frequency separation and a dual-side mode suppression ratio of more than 35 dB [34].

3. Optical switching matrixes

An interesting example of microwave applications using optics is optical phased array antenna control. The emerging direction of array antenna beam depends on delays or phases laws. It is defined by the path differences between the physical plane of the radiating components and the virtual plane perpendicular to the beam direction.

Delays, instead of phase shifts, are needed to insure frequency independent beam steering. Usually, true time delays are obtained by the use of coaxial links or microstrip lines. In this case, the limitations are antenna dimensions and instantaneous bandwidth. Optoelectronics is one of the most promising techniques that allows antenna to fit both aerodynamic requirements and whole space survey. Different methods were proposed : for example the use of high dispersion fibre in conjunction with a widely tunable optical source to obtain the required delay variation [35], or systems where polarisation switching spatial light modulators route the optical path directly or via a corner reflector to select the delay [36]. In one system studied by Thales TRT, signal delay is optically obtained by associating switching matrixes with fibres of different lengths. Architecture properties are characterized by both temporal dynamic and resolution. Due to losses, the critical point in such systems is the number of fibre to waveguide interfaces. Thus, in order to reduce losses one possible solution is to use architecture based on high order matrixes.

Numerous optoelectronic laboratories are currently enhancing technology and properties of such devices. In particular, Westinghouse has developed a true time delay system using microwave and optical technology [37]. Thales TRT proposes a system based on integrated switching matrixes. The use of guided optics allows high order matrix implementation. Moreover, light offers an additional dimension which is wavelength. If matrixes are strictly non-blocking, which means that each input can be connected to each output independently, this dimension allows a reduction in the number of switching components proportional to the number of optical wavelengths. With this architecture, it is possible to achieve more than 4000 different paths with four 8*8 matrixes. It is characterized by a temporal dynamic of 4 ns for a resolution of 1ps.

Key components of this system are switching matrixes that fit the following specific conditions:

- light polarization insensitivity
- strictly non blocking matrix
- equivalent intra-matrix path lengths
- low power consumption.
- low insertion loss
- low excess noise (phase noise)
- low cross-talk
- short switching time

Due to high speed switching requirements, electro-mechanical (MOEMS) or thermo-optic effects (polymers) cannot be used to fabricate the switching active elements. Semiconductor optical amplifiers (SOA) is an attractive way because of its capability to high cross-talk, compensation of insertion losses and high speed. But recent experiments performed at Thales TRT shown that this component increases strongly the phase noise of microwave signals [38]. Consequently solutions using electro-optic switches driven by electrostatic modulation, carriers depletion or injection must be explored.

Among possible materials, InP based are well established for 1.3 or 1.55μm wavelength applications. An optical switching matrix is a photonic integrated circuit associating monolithically passive elements (optical waveguide with bendings,...) and switching active elements. As an example, an InP optical waveguide, grown by MBE or MOCVD on n type InP substrate, is constituted of a GaInAsP quaternary core layer inserted between InP confinement layers with a lateral confinement obtained via a rib etching (figure 7).

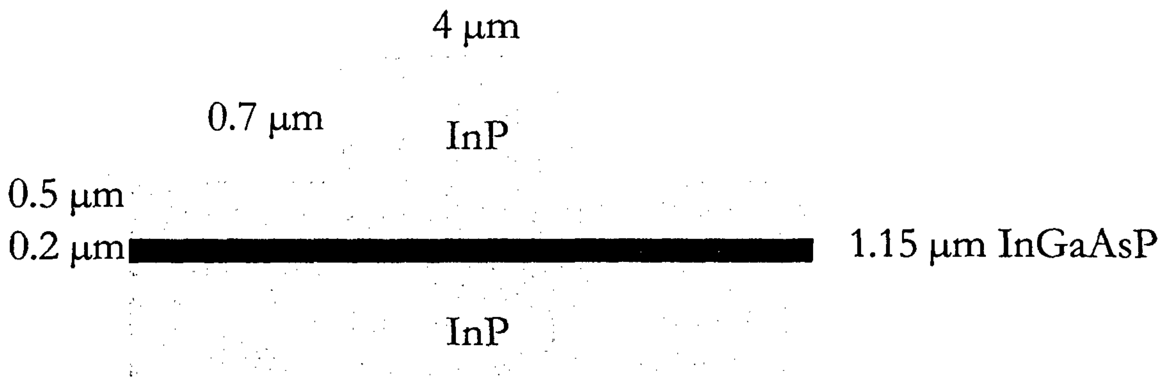


Figure 7 : Example of optical InP passive waveguide for switching matrixes.

About active elements, we used in devices fabricated at IEMN the plasma effect, obtained by injection of carriers in the optical waveguide, thanks to a PIN structure located by etching in the active zone. This effect decreases the optical index almost linearly with the density of carriers ($\cong 10^{-3}$ for 10^{17} cm^{-3}). We studied different structures : a kind of Electro-Optical Directional Coupler (EODC) that we called "cascade switch" [39-40] based on mode coupling, Digital Optical Switches (DOS) based on adiabatic mode changes [41] and a Total Internal Reflection (TIR) switch based on high reflection [42]. A 1 to 2 cascade switch (1 input, 2 outputs) is constituted of one active PIN waveguide placed closely between two passive waveguides playing the role of 1 input and 2 outputs. When no current is injected, the optical input beam is coupled to the extreme output waveguide. If current is injected into the current injection zone, the coupling is cancelled and light goes on the waveguide located just before the injection zone, here the input waveguide. This scheme can be extended to 1 to N optical switch: only one current injection will be required to obtain the light switch to any of the N outputs (figure 8).

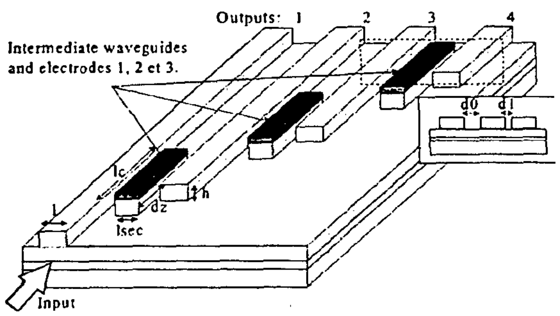
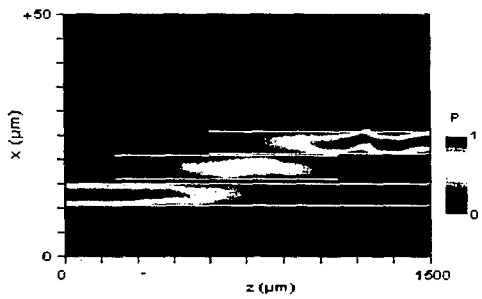
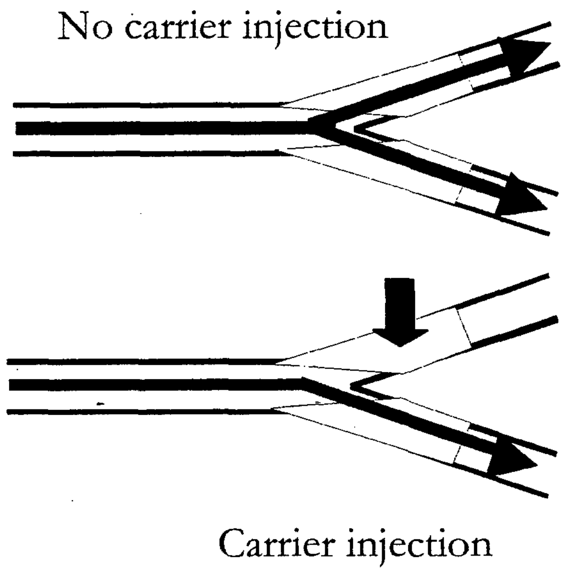


Figure 8 : Schematic view of a cascade switch



Modelling of light propagation (2D Beam Propagation Method) inside a cascade switch.

The technological fabrication [40] allows the monolithic integration of active and passive zones and is composed of three main steps: p ohmic contact realisation of the current injection zone, etching of the different guides, first level metallization and thinning and back N-metallization. The DOS is a Y junction with an electrode on each output arms. Without bias current the light is divided equally between the two arms. When a bias current is injected into one arm, optical index is reduced in this region, and light is pushed toward the other arm (figure 9).



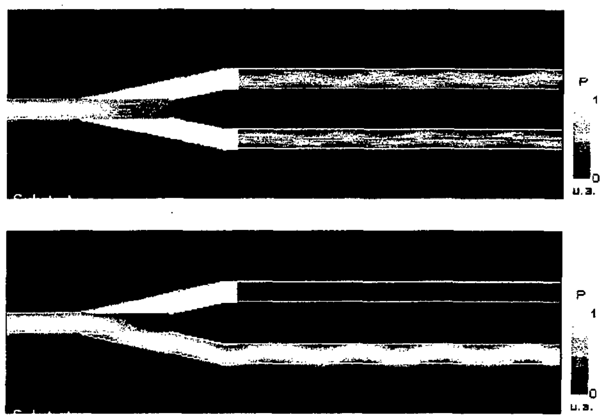
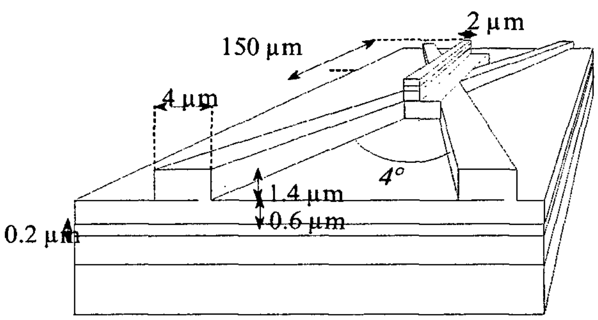


Figure 9 : Schematic view of a Digital Optical Switch

BPM modelling of the device.

The TIR is constituted of two crossing waveguides with an electrode at the crossing. Without biasing, light propagates along a straight line, an injected current acts as an electronic mirror and light is reflected into the other arm (Figure 10).



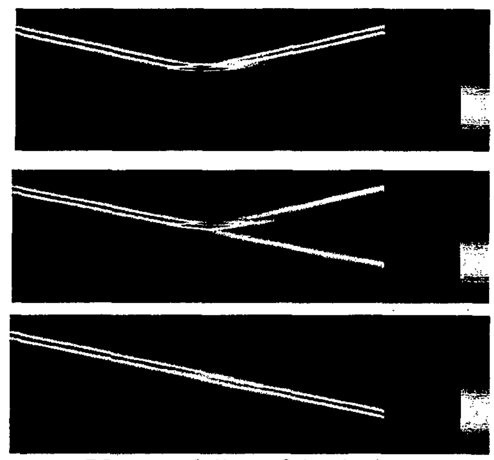


Figure 10 : Total Internal Reflection(TIR) switch

BPM modeling of the device.

. Our modelling and experimental studies show that:

- TIR switches suffer from a high consumption current (over 100 mA),
- Cascade switches offer optical cross-talk between 15-20 dB for current around 50 mA, with potentialities for 1 to N architecture with the same switching current, but suffer from a high sensitivity to technology,
- Best results are obtained with DOS. They exhibit the lowest switching currents (~20 mA for almost 1 mm long electrode and lower currents can be obtained with longer active zones) for optical cross-talk around 15 dB at 1.55 μm and around 30 dB at 1.3 μm wavelength (58 dB for a microwave signal at 9 GHz), figure 11.

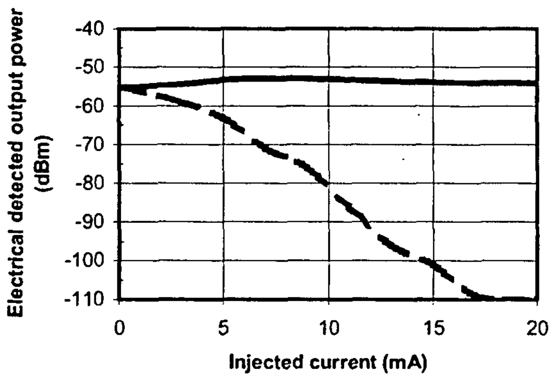


Figure 11a: Electrical output power of a 9 GHz signal issued from the switched on DOS branch (solid line) and the switched off one (dashed line) @ 1.3μm.

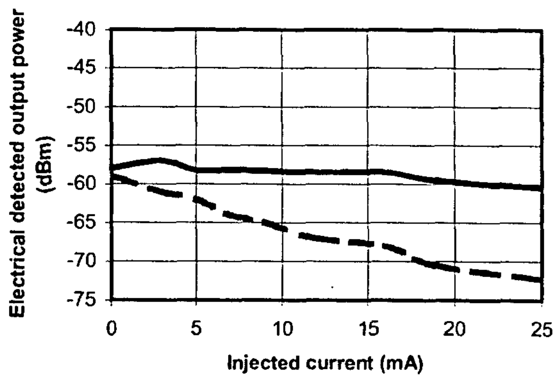


Figure 11b: Electrical output power of a 9 GHz signal issued from the switched on DOS branch (solid line) and the switched off one (dashed line) @ 1.55μm.

The difference between 1.55 μm and 1.3 μm wavelength cross-talk can be explained by band filling effects occurring for an operation wavelength close to the quaternary core layer bandgap wavelength [41] At last it was experimentally checked that the phase noise is not degraded by using DOS as shown on figure 12.

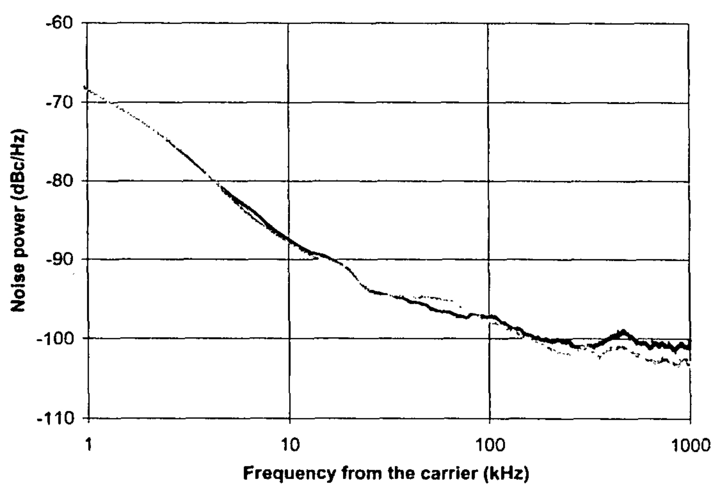


Figure 12 : Noise power level for at 9 GHz carrier@ 1.3 μm :
- gray line: switched signal (DC bias = 20 mA)
- black line: direct signal (DC bias = 0 mA)

4. High speed photodetectors

It is well known that high speed PIN photodiodes require short transit time in the active layer and small capacitance. As a consequence, for very high speed (millimetre wave) applications, the absorbing GaInAs region of InP photodiodes must be thin, typically 0.4 μm and less for cut off frequency higher than 60 GHz. With vertical illumination so thin absorbing layer leads to small quantum efficiency (figure 13a). The well known solution to overcome this trade off is the lateral illumination [43]. The photodetector is similar to an optical waveguide with an absorbing core, and is called PIN waveguide photodetector (figure 13b).

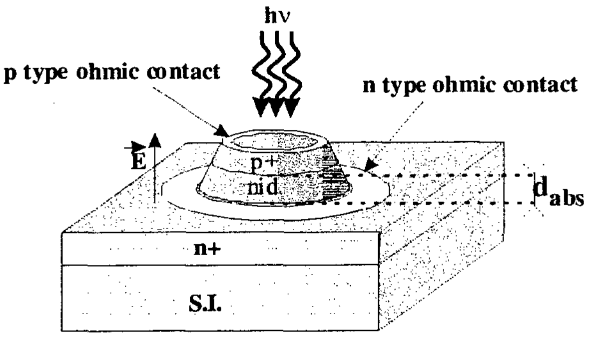


Figure 13a : Schematic view of a top illuminated PIN photodiode

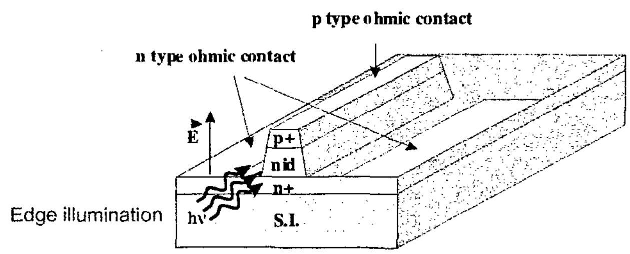


Figure 13b : Schematic view of a PIN waveguide photodiode

4.1 First problem: the optical coupling.

To get a good coupling to the optical fibre, a multimode structure is more suitable (figure 14). A typical epitaxy on InP semi-insulating substrate is then: a nid GaInAs absorbing layer between two (n and p types) GaInAsP and InP confinement layers, with a GaInAs p-type contact top layer. As an example, devices fabricated at IEMN exhibit a 4 µm etched rib waveguide, an input facet obtained by cleaving, with a total device length ranging around 10 to 20µm. With a lens-ended fibre, quantum efficiency higher than 60% without anti-reflection coating can be achieved with cut-off frequency over 60GHz [44].

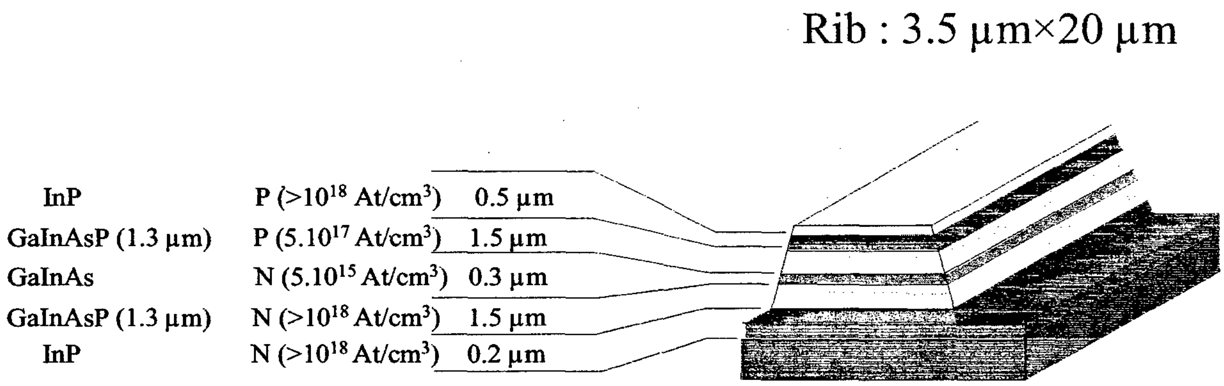


Figure 14 : multimode waveguide PIN photodiode

4.2 Second problem: the microwave or millimetre-wave access.

A semi-insulating substrate and a coplanar line improve the microwave access, by reduction of parasitics (capacitance ...) (figure 15). The semi-insulating substrate allows the monolithic integration of a passive reactive network with the PIN waveguide photodiode to reduce the large impedance mismatch between the PIN photodetector and the 50Ω of the microwave world in a small bandwidth, as experimentally demonstrated for 30 GHz operating frequency by Thales TRT, in collaboration with IEMN [45].

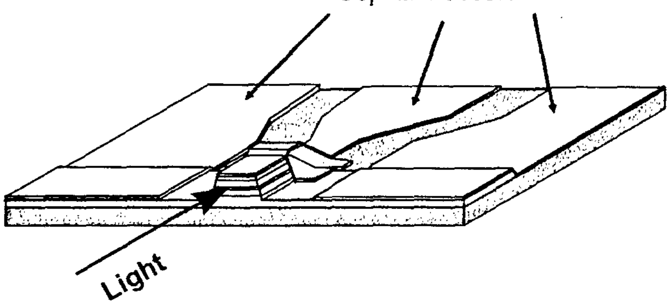
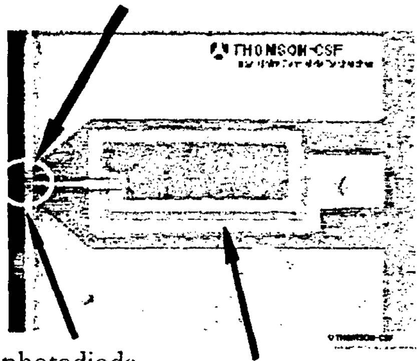


Figure 15 : coplanar microwave access.



Monolithic integration of
PIN waveguide photodiode and inductor

4.3 Third problem: the power.

Power limitation (≅ 0dBm at 60GHz) [46] occur in so small devices, due to high density of photocarriers killing the electric field in the intrinsic region and high photocurrent reducing the bias voltage in the external circuit. These effects reduce the dynamic of the link. To solve this problem, two ways are possible : the travelling wave photodetector with a long length (and hence volume) with electrodes designed to get a 50Ω microwave line, and the uni-travelling carrier photodetector (figure 16) for which photodetection takes place in a thin p-type highly doped GaInAs absorbing layer. Up to date results are very encouraging [47, 48] and works are in progress at IEMN in collaboration with Thales TRT and Alcatel to get high speed, high power and high quantum efficiency devices.

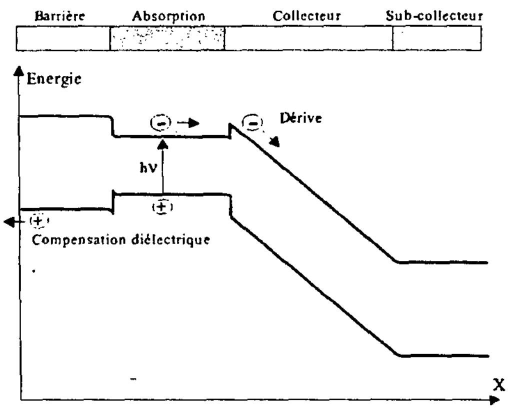


Figure 16 : band structure of an UTC photodiode.
Only electrons pass through the collector.

4.4 Fourth problem: the reliability.

The direct illumination scheme used in these devices has some known impairements: input facet fabrication with junction passivation is difficult to achieve with high reliability [49]. To overcome these impairments, high speed edge illuminated, evanescently coupled PIN photodiode was demonstrated [50]. For this last device, a taper was included in the input waveguide, leading to better alignment tolerance to the fibre. But the tapered waveguide exhibits excess loss which reduces the sensitivity. It is the reason why an attractive way is the use of a diluted multimode input waveguide, followed by the evanescently coupled PIN photodiode. The diluted waveguide is made of very thin GaInAsP quaternary epilayers introduced in InP.

The distance between the quaternary epilayers decreases from the substrate to the top of the waveguide to get a specific waveguide which can be compared to a half lens whose centre is on the top of the waveguide (figure 17). Due to numerous technological parameters and targeted performances, the device was optimised at IEMN using genetic algorithm coupled to a 2D – BPM [51]. It was fabricated at Opto+ and experimental results shown that high responsivities (≅ 1 A/W), low polarisation dependence (<0,5 dB) and high alignment tolerance (≅ ± 2μm) can be achieved at 1,3 and 1,55μm wavelength [52]. The cut-off frequency is in excess of 3GHz and works are in progress to extend the bandwidth up to the millimetre wave frequency range.

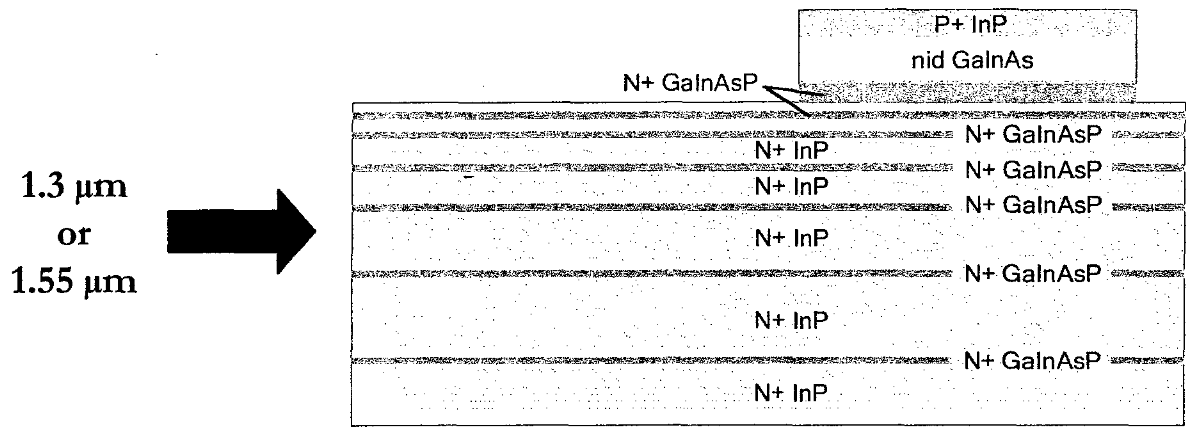


Figure 17 : multimode evanescent coupled PIN waveguide.

5. Specific microwave photonic functions: up and down conversion

5.1 Principle:

Up or down conversion is based on the existence of a non-linear element in a circuit. This element can be purely electrical and associated to the optical (or optoelectronic) component or circuit, or inside the optoelectronic component itself. We will examine various examples of non-linear functions at the emitter stage or receiver stage, demonstrating their ability for up or down conversion. The characteristic parameter is the gain conversion, which represents the comparison between the intensity of the converted line to the signal line. The goal is here to get a gain conversion (and hence a non-linearity) as high as possible.

5.2 Emitter stage:

Semiconductors lasers can be non-linear (under particular conditions such as high bias current or signal frequency close to the resonance frequency) but their characteristics are also degraded (noise...). To enhance non-linear effects and keep a good quality of emitted signals, other solutions are possible such as the association of a laser diode with an external modulator. The microwave signal is applied onto the laser and the second one onto the optical modulator. By doing this, the amplitude of the optical signal is modulated two times and contains the product of the two microwave signals amplitude. As a consequence, we find at the output of a high speed photodetector the two lines of the applied microwave signals, but also the sum and the difference of these two frequencies. Derived solutions are for example based on the use of one CW laser diode associated with two external modulators in series to apply the microwave signals. Monolithic solutions are also possible with (commercially available) DFB laser integrated with an electroabsorption modulator.

Another monolithic possible solution is the use of two-electrode lasers presented in section 2 for their enhanced dynamic response. The basic principle is to apply a microwave signal on each electrode with frequency respectively f_1 and f_2. Since the power-current characteristic depends strongly on the voltage applied onto the short electrode, the output signal will be strongly non-linear and at the output of the photodetector we measure the beat between the two frequencies. Our experiments have shown that the conversion gain ranges from -3 dB to –17 dB [53].

5.3 Receiver stage:

Photodetectors are in general linear devices (except under high power and low bias voltage, see before). It means that it seems difficult to use them directly as up or down converters. It is the reason why most of the solutions at the receiver stage are based on the association of a specific electrical (microwave) circuit to the photodetector. The optoelectronic component is then considered as a microwave signal source and the up or down conversion is made electrically with classical microwave techniques. Since many optoelectronic components are now based on InP materials (1.55 µm and 1.3 µm wavelength), their monolithic integration with microwave circuits (MMIC) is impossible, except if devices suitable for 0.8 µm wavelength are accepted. As an example, a possible solution is a specific integrated circuit associating Metal-Semiconductor-Metal GaAs photodetector with a dual gate MESFET. In spite of a rather low quantum efficiency due to shadow effects of electrodes, GaAs MSM photodetectors are known as high speed devices for 0.8 µm wavelength applications, with easy monolithic integration with field effect transistors. The use of dual gate MESFET allows to enhance the non-linear effect of the transistor and to separate the two input ports corresponding to the two microwave signals to be mixed. In this MOMIC (Microwave Optical Monolithic Integrated Circuit) fabricated at IEMN, one gate is electrically connected to one electrode of the MSM exactly as a PIN-FET and the other gate is used for the second microwave signal. The ability of this integrated circuit to up or down convert the frequency of microwave signal modulating the optical signal detected by the MSM photodetector was experimentally demonstrated [54] with conversion gain around –3 dB at 10 GHz.

The objective to monolithically integrate the non-linear microelectronics with the photodetector whatever the optical wavelength (0.8 µm, 1.3 µm or 1.55 µm) is, led to use an heterojunction phototransistor (HPT) as optoelectronic mixer. This device can be considered as a high speed photodetector with internal gain due to transistor effect. It is also an heterojunction bipolar transistor (HBT) with a base-collector junction used as a photodiode and combines monolithically the properties of an HBT and a photodiode. High speed transistor and photodetector are obtained with short transit time in GaInAs p+ base and n- collector layers. Although high speed demonstrations were made with top illuminated devices, edge illumination is suitable for high quantum efficiency and millimetre wave operation. Following previous works [55], this scheme was adopted at IEMN, since epilayers structures are compatible with an optical waveguide. For the devices fabricated at IEMN, a GaInAsP quaternary layer was introduced between GaInAs collector and InP sub-collector to get a multimode waveguide, figure 18. No quaternary layer was introduced in the emitter-base junction to keep its electrical properties. As expected, this device is a millimetre wave photodetector with internal gain (≅5dB at 40GHz) and high quantum efficiency (60% without AR coating) [56, 57]. But it is also an efficient optoelectronic mixer thanks to the non-linear behaviour of the transistor under suitable bias voltage [56, 57, 58]. More precisely, experiments carried out with a 1 GHz modulated optical signal, different optical powers (from 0 to 1 mW at the output of the fibre) and electrical DC base bias currents, shown an improvement of more than 30 dB for very small optical powers which can be explained by the gain non-linearities of the device.

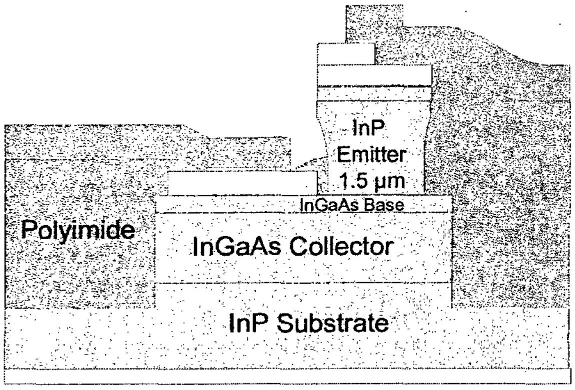
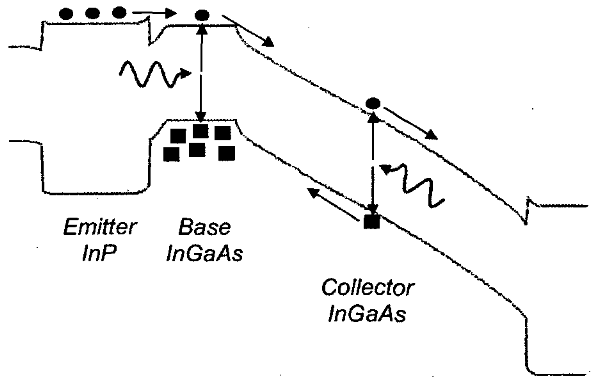


Figure 18 : Schematic view of a heterojunction phototransistor with base contact (3T-HPT).



Band structure of a heterojunction phototransistor.

These non-linearities can be used to mix an amplitude modulated optical signal with an electrical one applied on the base terminal. Figure 17 shows the result of such an experiment. The intermediate frequency (IF) of the modulated optical signal is 1 GHz (with a 10 dBm power on the laser) and the local oscillator frequency (LO) is 18 GHz (with a power level of -20 dBm applied on the base). The electrical spectrum exhibits the central band at 18 GHz and the two first sidebands at 17 GHz (LO-IF) and 19 GHz (RF=LO+IF).
Another experiment was carried out with IF=8 GHz (0 dBm on the laser) and 500 MHz < LO < 10 GHz (with a power level of -10 dBm). The up-conversion gain (compared to the base-collector junction) versus LO and LO+IF is presented on figure 19. The HPT optoelectronic mixer exhibits a 6 dB up-conversion gain around LO=500 MHz and gain can be observed up to LO=7 GHz.

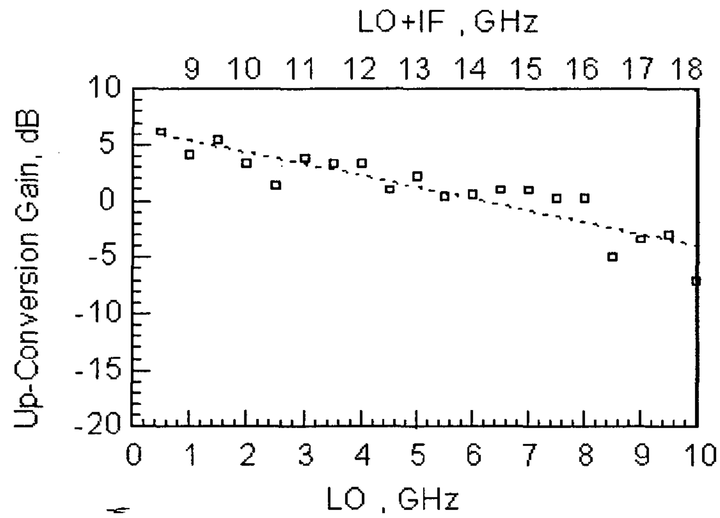


Figure 19 : Conversion gain (compared to the base-collector junction) of the mixing between an optical signal modulated at IF=8 GHz and an electrical signal applied on the base modulated at 500 MHz<LO<10 GHz (power level of -10 dBm).

For comparison, Lui, Seeds and Wake [58] reported down-conversion using a two-terminals edge-coupled InP/InGaAs HPT, with a maximum 7 dB down-conversion gain when IF=500 MHz, RF=2.5 GHz and LO=3 GHz. Suematsu *et al.* [59] reported a top-illuminated three-terminals HBT up-converting mixer with a conversion loss of 4 dB when IF=3.2 GHz, RF=30 GHz and LO=26.8 GHz. These experiments show that InGaAs / InP HPTs are promising devices to transmit a data signal up-converted to a millimetre-wave signal thanks to a mixing with a signal delivered by a local oscillator. More recently, C. Gonzales [60] and G. Eisenstein [61] demonstrated also very efficient mixing experiments using HPTs.

6. Hybrid versus monolithic integration

Microwave Monolithic Integrated Circuits are now fabricated in GaAs foundries and allow to associate, on the same substrate, a lot of different passive or active components, to get a given or several microwave functions on the same chip. Monolithic integration leads to a lot of advantages : compactness, reduction of parasitics, increasing functionality... and we could hope to get the same advantages from the monolithic integration of optoelectronic or photonic components, with microwave components to get Microwave Optoelectronic Monolithic Integrated Circuits (MOMICs). This is possible in pure microwave circuits because there is a technological compatibility (epitaxy, process...) between the various components of a MMIC. Unfortunately, this technological compatibility does not exist between the various optoelectronic (and microwave) components. For example, the structure of a high speed laser is completely different to the one of a PIN photodetector or field effect transistor. It is the reason why, in spite of a lot of technological works and researches in this field, it exists only a few examples of mature (industrial) photonic or optoelectronic integrated circuits. A well known (and may be to date the only), commercially available photonic integrated circuit, is a DFB laser integrated to an electroabsorption modulator. Even in this modest circuit (two components) complex technological steps are required. Optoelectronic circuits, associating optoelectronic components and microelectronics are not commercially available. This situation is due to completely different epitaxial structure for the optoelectronic components (2-3 μm thick) and microelectronic components (0.1 μm thick for a field effect transistor). The most advanced optoelectronic integrated circuits are probably those based on the integration of an Heterojunction Phototransistor and Heterojunction Bipolar Transistor, because these devices have the same structure, except some geometrical aspects. Here the epitaxy and the process are almost the same. The difference between microelectronic and optoelectronic devices is controlled by the design of the mask. Several high speed photoreceivers and non linear photo-mixers or photo-oscillators were experimentally demonstrated, but up to now, to our knowledge, no optoelectronic integrated circuit is commercially available.

The consequence is that optoelectronic industry has chosen the way of self-aligned flip-chip mounting technique on silicon mother-board. The basic idea is here to fabricate each component (optoelectronic, photonic...) needed for a circuit, using mature single component technology and to assemble them on a specific silicon substrate. The main problems are then: how to align the optical (optolectronic) components along the same optical axis and how to make the electrical (microwave) connections.

The first difficulty was solved using preferential silicon etching. The silicon substrate carries preferentially etched V-grooves with the angle α =54.74° between the (100) and (111) crystal planes. Passive alignment of single mode fibre and waveguide devices can then be achieved. Photolithography of Si mother board allows the precise etching of V-grooves for the fibre alignment and other V-grooves for the positioning of the waveguide device. To get the alignment compatibility of the photonic device with the silicon mother board, special alignment indentation, self aligned with the waveguide stripes are achieved on the chip in the III-V material photonic device [62].

The second difficulty resides in the electrical (microwave) interconnection. One technique, compatible with the mother-board self aligned packaging, is to etch a V-groove in the silicon designed to include electrical transmission lines and solder stripes to contact and fix the electro-optic waveguide device. To reduce parasitics, the flip-chip interconnection can use small solder bumps (~20 μm in diameter). It allows to connect the pads of the two chips face to face, and operation up to millimetre frequency range occurs if no other effects introduce frequency limitations [63, 64].

7. Conclusion

Good performance improvements were obtained for various microwave optoelectronic and photonic devices during these last 10 years. Nevertheless, further works are still needed to fulfil all system requirements, for example: low noise laser, high bandwidth and low drive voltage optical modulator, high linear emitters and receivers, high speed - high cross talk – low consumption and insertion loss optical switching matrixes... No doubt that, by using together recent technological advances and modelling tools, and, may be, new concepts, it will be possible to reach these goals.

Another main aspect of the microwave photonic functions is to take advantage of hybrid or monolithic association of components to reduce parasitics, improve compactness, increase the functionality... Knowing that technological compatibility does not exist, the industrial production of Microwave Optoelectronic Monolithic Integrated Circuits, seems to date difficult, except may be for very special cases. It is the reason

why in most mature microwave photonic systems, it is more reasonable, particularly for millimetre wave applications, to reduce the difficulty of the photonic part by an increase of the complexity of the microwave (millimetre wave) part, since MMICs are commercially available. Nevertheless, with the appearance of new technological tools, it becomes now possible to fabricate very confined (sub-micron) optical waveguides, which corresponds to a reduction of 10 of the size of the waveguide (100 in section area). We can then imagine designing very small photonic components and integrated circuits which sizes are compatible to those of MMICs, with low consumption and high efficiency, and by techniques like polymer wafer bonding to associate a photonic (optoelectronic) integrated circuit with a MMIC.

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